XIV NASAS: Fatigue, Fracture and Ageing Structures; Eds.: CM Manjunatha, VR Ranganath, RK Paretkar and DR Peshwe, 30-31 January 2006, Visvesvaraya National Institute of Technology, Nagpur, pp. 185-190.

Failure of Life Extended Rotor Discs of Aeroengines

M Sujata, MA Venkataswamy, MA Parameswara, M Suresh Kumar and SK Bhaumik*
Failure Analysis Group, Materials Science Division, National Aerospace Laboratories, Bangalore 560 017

Abstract

Over the past decade, aircraft readiness rates have declined, spare parts have been in short supply, and the cost of the turbine engine maintenance has escalated manifold. As a result, aircraft manufacturers and the operators throughout the world have embarked on an initiative to address sustainment of currently used turbine engines. The initiative is known as engine rotor life extension (ERLE) programme. Among the various fracture critical components of an aeroengine, rotor disc represents an immense asset, thus discarding them prior to expiration of full useful life causes a tremendous burden on the gas turbine engine budget. Various approaches have been adopted to reassess the total useful life of a turbine rotor disc which mainly include (i) increasing the accuracy of the low-cycle fatigue life prediction methodology and (ii) increased confidence in the inspection process to locate smaller cracks and internal flaws. Combined with these, reworking of the discs has also been attempted. A couple of case histories on the failure of rotor discs are presented in this paper wherein reworking was carried out for extension of life. In both the cases, the failure resulted in accident. The critical aspects that are to be looked into to prevent failures in the extended life of such reworked components are discussed.

Keywords: Compressor rotor disc; Turbine rotor disc; Life extension; Fatigue failure

1. Introduction

The compressor and turbine discs, and shafts of an aeroengine are fracture critical components since their failure in service affects the safety of the aircraft. These components are subjected to severe cyclic stresses and hence in the absence of an adequate life prediction policy, they eventually undergo low cycle fatigue failures. In the past, most of these components were designed based on safe-life criterion (SLC), wherein the cycle life limits of the component are established by statistical analysis of all the available specimen and component life data to provide an acceptably low probability of service failure[1]. In most of the aircraft programmes, the safe life is defined as the time span after which one in 1000 or 750 discs is expected to have fatigue induced crack of approximately 0.75 mm length. It has been estimated that with the use of SLC, about 90% of discs are removed from service having consumed less than 50% of their safe-life capability[1-3]. As a result, an alternative approach involving retirement for cause (RFC) and damage tolerant design (DTD) were evolved wherein controlled fracture permits a significant safe flight time after the onset of initial crack or other types of damage. These two approaches were adopted for analysis of existing engine components and design of new components respectively. The implementation of the above criterion was dependant on the designer's ability to ensure that catastrophic large crack growth would not occur between inspections and that the final crack size would not endanger the integrity of the component. This concept, known as the fail-safe condition, was achieved either by ensuring structural redundancy for load sharing or load shedding, should catastrophic failure occur. Nevertheless, in view of the huge costs spent on generating large amount of data required to support these approaches, various schemes were derived by the manufacturers to improve the service life of the component, reworking being one of them.

* Tel: 080-2508 6277, Fax: 080 – 2527 0098; e-mail: subir@css.nal.res.in

2. Life extension Methodologies

Boyd-Lee et al[2] have reviewed the various component life extension methods used by exploitation of non-finite results which yield life extension by 20% and exploitation of crack tolerant geometries via fracture mechanics approach that can yield life extension of upto 50% of engine flying hours. Life extension methodologies are based on risk assessment. Risk assessment is done based on inspection and some times, it is based on statistical modeling of the specific sources of component life uncertainty. Studies show that actual safe service life of a component can be more strongly determined by the probability of crack detection than by minimum detectable crack size.

3. The Life Limiting Mechanisms in Rotor Discs

The life limiting mechanisms of different aeroengine components vary from the compressor to the turbine section. For instance, in a compressor, for components that operate at relatively higher temperatures (in the range 500-600^{0}C), the life limiting mechanism is fatigue crack initiation followed by environmental accelerated fatigue wherein the stress intensity range is modified due to creep-fatigue interactions. For cooler components, combined low cycle fatigue (LCF) and high cycle fatigue (HCF) usually limit the life[2].

Meguid et al[1] have carried out stress analysis using finite element modeling on the dovetail regions of compressor discs. These studies conducted typically for titanium alloys, show that peak values of contact stresses at the dovetail-blade interface occur at the lower contact point of the blade. Their study showed that the magnitude of the maximum stress concentration is influenced by the inner fillet radius, flank length and coefficient of friction[1].

The components that operate at high temperatures such as the turbine blades and discs and the combustion chamber are designed such that the limiting life is dictated by creep damage under thermo-mechanical loading[2].

In the case of an aeroengine rotor discs, lifetime certification is necessary in three critical areas. These include (i) dovetail-rim region, (ii) the assembly holes and (iii) the hub region. It is now established that in majority of the cases, cracks are initiated in the dovetail region due to the fretting action at the blade-disc interface[1].

4. Life Extension of Rotor Discs Through Reworking

Analysis of 3D thermo-mechanical state in aeroengine components is essential to calculate accurate service life. Life extension philosophies are based on risk assessment in terms of optimization of safety, affordability and operational flexibility. In spite of all these, premature failures of components can result from inadequacies in risk assessment. As far as the reworking on the discs are concerned, it is important to note that the reworking is carried out in critical locations where the vulnerability exists for the presence of incipient fatigue cracks and service induced mechanical damages. Alteration of surface properties such as the residual stresses is also an important criterion. If enough care not taken, defects introduced during reworking can have serious weakening effect on the component. These can facilitate early nucleation of fatigue cracks and thereby jeopardize the safe service life of the components. Design modification or ad-hoc modification is also being practiced occasionally for extending the life of rotor discs. Sometimes even a carefully conceived and thoroughly evaluated design may still be deficient and can contribute to unanticipated failures in service. These are illustrated with suitable case histories in the following sections.

5. Case Histories

A couple of case histories on failed rotor discs of aeroengines are presented wherein reworking was carried out for extension of life. In both the cases, the failure resulted in accident.

5.1. Failure of a Compressor Rotor Disc

An aircraft met with an accident due to engine failure. Investigation revealed that failure of the compressor disc was responsible for the accident. The compressor disc was made of titanium alloy of specification IMI550. The disc had a total technical life of 1500 hrs. However, after 1300 hrs in service, the disc was withdrawn for life extension. A thorough non-destructive examination (NDE) was carried out to assess the health of the disc and the disc was cleared for life extension of 500 hrs after a minor reworking at the dovetail fillet region. It was reported that the reworking was carried out on the disc wherein the dovetail root radius was increased marginally by machining operation. The failure took place after 60 hrs in the extended life.

Figure 1 shows the failed compressor rotor disc. The disc had fractured into two pieces; the smaller segment had three dovetail slots, while the larger one had sixteen slots. Fractographic study confirmed that the disc had failed by fatigue (Fig.2). The fatigue crack had initiated at the dovetail fillet region at the trailing edge and propagated at an angle towards the leading edge across the thickness of the disc. No metallurgical abnormalities and/or mechanical damages were observed at the fatigue crack origin. Fluorescent dye penetrant inspection of the fractured pieces revealed three more cracks at the dovetail slot Nos. 5, 8 and 15. These were also fatigue cracks and the crack origin in these cases was identical to that mentioned above.

It may be noted that the disc was in service for 1300 hrs and no cracks were reported to have developed in the disc during this service period. This was confirmed by NDE before life extension. Hence it could be conclusively stated that fatigue crack nucleation and propagation to a critical length had occurred within the 60 hrs of service in the extended life. Also, the possibility of any metallurgical abnormalities in the disc material could be eliminated. It was convincing to arrive at the conclusion that the fatigue crack initiation was stress related. This was further substantiated by the presence of fatigue cracks in a number of dovetail slots at identical locations.

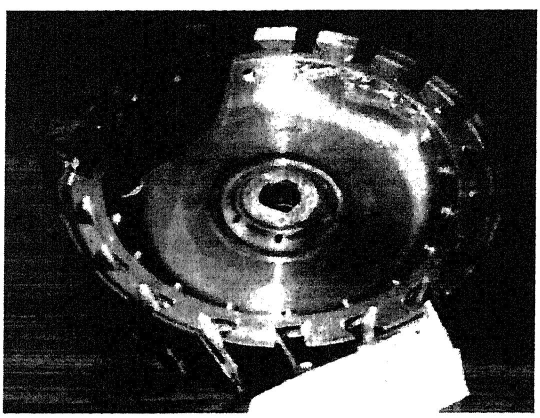


Fig. 1. Fractured compressor rotor disc

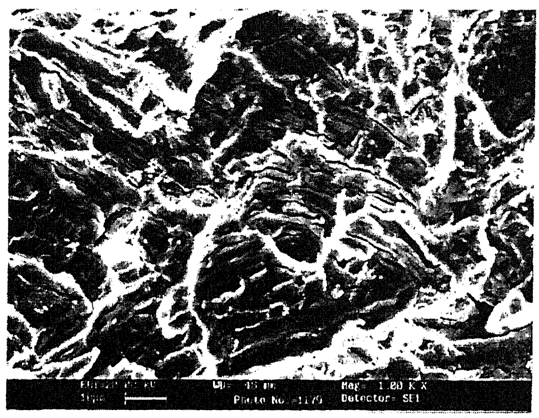


Fig. 2. Fatigue striations

Based on the above analysis, it was apparent that some defects might have been introduced in the disc during reworking which facilitated the fatigue crack initiation. Either they are mechanical in nature such as the stress raisers or residual stresses. Examination did not reveal any mechanical abnormalities and in fact, the dovetail root radius and the surface finish were found as per the reworking specification. However, stress measurements through X-ray technique showed presence of residual tensile stress of about 400 MPa in the dovetail fillet region. The measurements performed on all the uncracked dovetail slots unambiguously confirmed this finding.

It is to be noted that the design specification calls for micro-shot peening operation at the dovetail root region for two reasons. Firstly, this is necessary to eliminate the residual surface tensile stresses introduced during machining operation and secondly, to introduce residual compressive stresses for enhancing the fatigue life of the component. Investigation clearly established that during reworking, the micro-shot peening operation was omitted. Deficiencies of this type can generally be related to inaccurate, incomplete or ambiguous reworking specifications, but they also can occur as a consequence of human error or negligence.

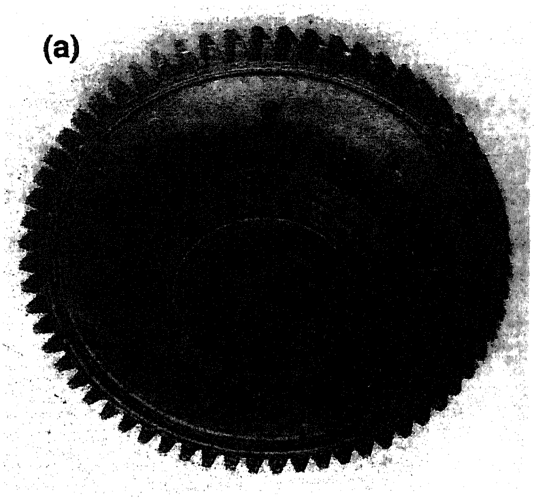
The above example amply illustrates that during reworking, the component is vulnerable to all those defects, which could have been introduced during fabrication itself. Hence it is of utmost importance that the specification and inspection schedule laid down in the original fabrication procedure are followed during the reworking as well. Any error at this stage jeopardizes the airworthiness of the component as seen in the present case.

5.2. Failure of a High Pressure Turbine Rotor Disc

There was an aircraft accident due to failure of the high-pressure turbine rotor (HPTR) disc. The failure was traced to the detachment of the labyrinth. Generally, labyrinth is an integral part of the HPTR disc. Statistics show that a large number of the HPTR discs are withdrawn from service prematurely, i.e., before completion of the total technical life because of the wear out of the labyrinth. This results in huge financial burden on the aircraft operators. To utilize the useful life of the disc effectively, the engine manufacturer suggested an ad-hoc modification of the disc. A reworking scheme was recommended wherein the worn labyrinth was machined out from the disc and a separately fabricated labyrinth ring was interference fitted on to the hub of the disc. The labyrinth ring was located with the help of 60 pins. In this particular case, it was such a reworked disc with a life extension of 1000 hrs. The failure took place after 850 hrs of service in the extended life.

Figure 3 shows the HPTR disc and a part of the detached labyrinth ring. Investigation revealed that the detachment of the labyrinth ring from the disc was the first in the chain of events that led to accident of the aircraft. All the pins used for locating the labyrinth ring were found fractured/sheared.

(a)



(b)

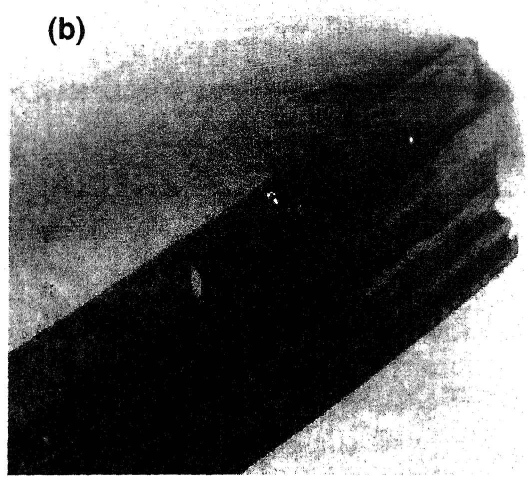


Fig. 3. Photographs showing (a) HPTR disc and (b) a part of the detached labyrinth ring

A few pins were taken out from the disc and the fracture surfaces were examined. Fractographic study confirmed that all the pins had fatigue cracks (Fig.4). Analysis showed that the axial movement of the labyrinth ring resulted in deformation of the pins at the ring/disc interface. The stress raiser thus resulted was responsible for the fatigue crack initiation. Hence it was recommended that engines with similar reworked HPTR disc be withdrawn from service and the pins be subjected to examination to look for fatigue cracks, present if any. Following this, six engines with different service lives of the HPTR discs were withdrawn and the pins were subjected to fluorescent dye penetrant inspection. Fatigue crack was identified in majority of the pins that had completed in excess of 220 hrs of service. In all the cases, the fatigue crack was associated with a circumferential depression mark (Fig.5). This study confirmed that there was axial movement of the labyrinth ring in all the reworked discs. It was also proved that such axial movement is unavoidable, and hence the structural integrity and airworthiness of the reworked discs are not acceptable.

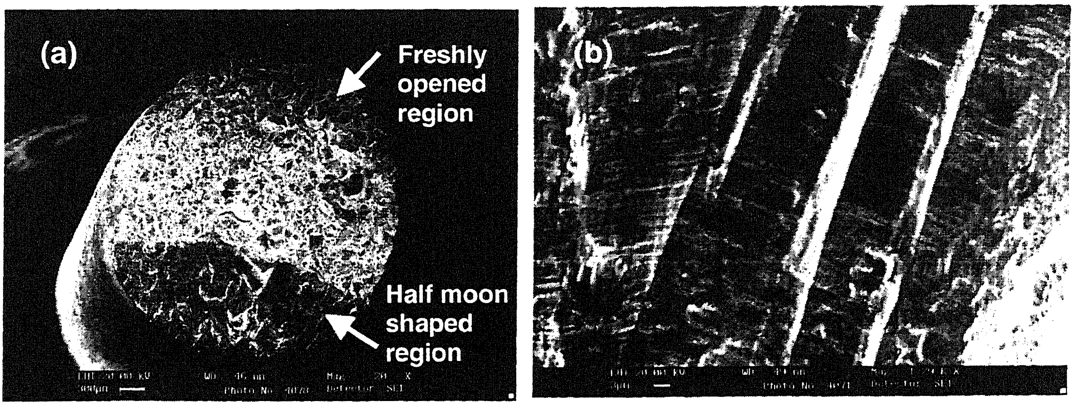


Fig. 4. (a) Fracture surface of a typical pin and (b) scanning electron fractograph showing fatigue striations

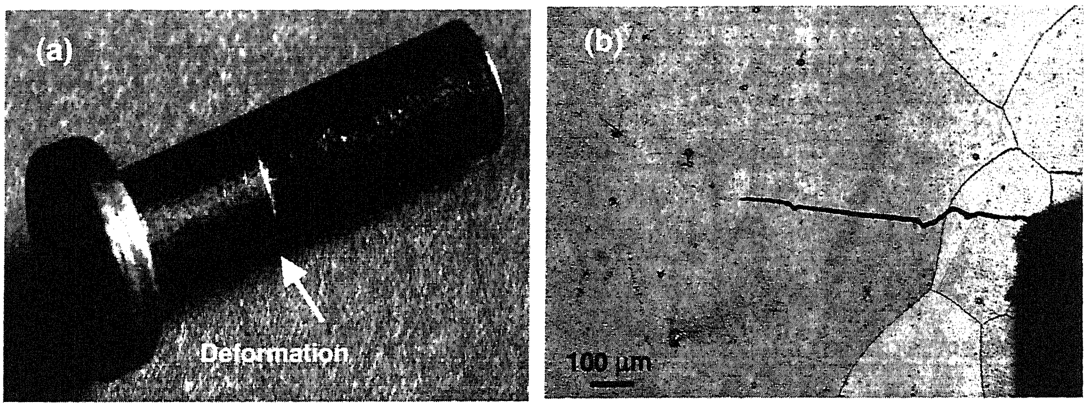


Fig. 5. (a) Photograph showing circumferential deformation on the pin and (b) cross section of the pin showing fatigue crack at the deformation mark

Analysis showed that the ad-hoc modification scheme had following deficiencies: (i) inadequate design to prevent axial movement of the labyrinth ring and (ii) no accessibility for inspection of the pins. It was surprising to note that while the HPTR disc had mandatory inspection schedule in every 500 hrs of service, there was no inspection in the reworked region, probably because of the inaccessibility.

6. Conclusions

It has been demonstrated that if enough attention is not paid during reworking scheme, things can go wrong beyond anticipation. Many a times, the structural integrity of the components is inadvertently compromised to an unacceptable limit. It is mandatory that for life extension of fracture critical components such as the rotor discs, the risk factor analysis has to be adequately stringent and it must be built upon sufficient redundancy.

Acknowledgements

The authors thank Mr. C.R. Kannan and Ms. Kalavathi for NDE and scanning electron microscopy support. The help rendered by Mr. Keshab Barai for metallographic sample preparation is acknowledged. The authors are thankful to Director, NAL for permission to publish this work.

References

1. S.A. Meguid, M.H. Refaat and P. Papanikos, *J. of Materials Processing Technology*, **56**, 1996, 668-677
2. A.D. Boyd-Lee, G.F. Harrison and M.B. Henderson, *Int. J. of Fatigue*, **23,** 2001, S11-S19
3. G.F. Harrison, P.H. Tranter, D.P. Shepherd and T. Ward, *Mater. Sci. and Engg.,* **A365,** 2004, 247-256